ENERGY MANAGEMENT IN A VEHICLE WITH A DUAL STORAGE POWER NET

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Abstract: In the near future, a significant increase in electric power consumption in vehicles will occur. To limit the associated increase in fuel consumption and exhaust emissions, smart strategies for the generation, storage/retrieval, distribution, and consumption of electric power will be used. This paper deals with an advanced power net with two storage devices: a lead-acid battery and a super capacitor, whose advantages can be combined. Two methods to control such a power net are presented: global optimization using full knowledge of the future driving pattern and an online implementable strategy doing without future knowledge. Both methods involve mixed integer optimization. The performance of the real-time strategy is close to the global optimum.

Keywords: Automotive control, energy management, mixed integer optimization

1. INTRODUCTION

The electric power consumption in standard road vehicles has increased significantly over the past twenty years (approximately four percent every year) and in the near future, even higher power demands are expected (Nicastri and Huang, 2000).

To handle future power demands, the automobile industry has proposed a new 42V power net topology which should replace the traditional 14V power net from present vehicles (Kassakian *et al.*, 2000; Nicastri and Huang, 2000). Although these advanced power nets will be able to meet tomorrow's power requirements, a problem that arises is how to control the power net, in order to reduce the fuel consumption of the vehicle.

Continuing on previous work (De Jager, 2003; Koot *et al.*, 2004), that focus on vehicles with one storage device, this paper considers an advanced power net as proposed in (Sebille, 2003) with two storage devices: a lead-acid battery and a super capacitor. The reason for using two storage devices is to combine their advantages. The supercap seems especially suitable for storing peak powers that occur during regenerative braking.

Two methods to control such a power net are presented: global optimization using knowledge of the complete driving cycle and an online implementable strategy doing without future knowledge.

The control strategy acts as a supervisory controller, that specifies the desired power flows. Lower level component controllers are needed to implement the desired power flows.

This paper is built up as follows: The vehicle power net topology will be described and analyzed in Section 2. In Section 3, the energy management control problem is formulated. The system is modeled in detail in Section 4. A global optimization method will be presented in Section 5 and a real-time control strategy in Section 6. Their performance will be compared by simulations in Section 7. Conclusions are given in Section 8.

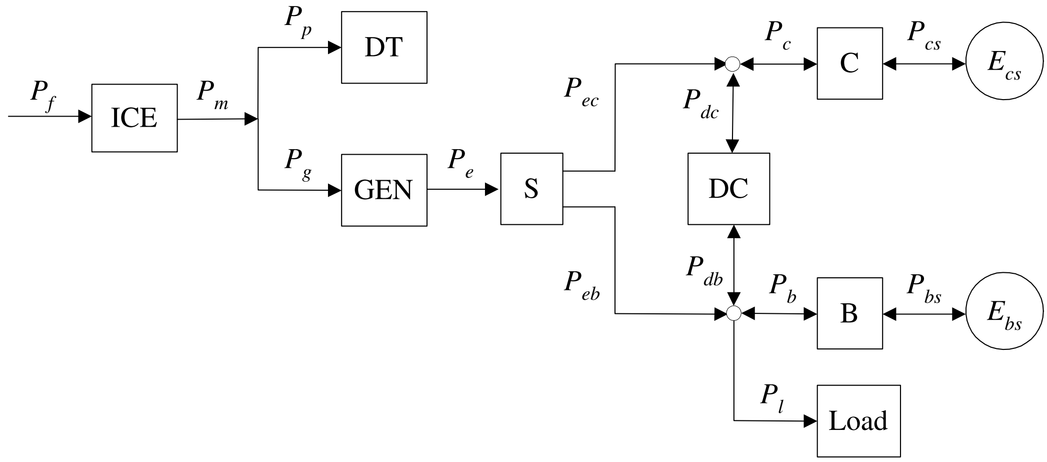

Fig. 1. Power flow in a dual storage power net

2. DUAL STORAGE POWER NET

This paper considers a conventional vehicle with manual transmission. It is assumed that the vehicle speed and the gear ratio are controlled by the driver, such that the engine speed and the mechanical power needed for propulsion are predefined as well as the electric load request.

The electric part of the vehicle is an advanced dual storage power net, consisting of a generator, a switch, a battery, a supercap and a DC-DC converter. The generator and the DC-DC converter are power controlled.

The reason for using two storage devices is to combine their advantageous properties, see also (Baisden and Emadi, 2004) for a comparison.

The battery has a large capacity and small energy leakage over time. However, the losses during charging and discharging and battery wear are large, especially when using high powers.

The open cell voltage of the battery is linear with the energy level but with a large offset. Because of this offset, the battery can be operated between 20% and 100% state of charge (SOC) while maintaining an acceptable board net voltage.

The supercap has a smaller capacity, but the charge and discharge losses are also much smaller. This makes the supercap advantageous to use for high peak powers. A supercap has considerable energy leakage, so it is not suitable for long term storage.

The open cell voltage of the supercap is linear with the energy level. If the supercap is connected directly to the board net, it can only be operated within a small SOC window while maintaining an acceptable board net voltage. By connecting it to the board net using a DC-DC converter, it can be used in its full range.

2.1 Power flow

The power flow in the vehicle is shown in Fig. 1.

The power flow in the vehicle starts with fuel that goes into the internal combustion engine (ICE) which converts it into mechanical power. One part goes to the drive train (DT) for vehicle propulsion, whereas the other part goes to the generator (GEN) which converts it into electric power.

The generator is connected to a switching device (S) that divides the electric generator power between the supercap (C) and the battery (B). The switch can be a discrete switch or a continuous power divider. The battery and the supercap are connected to a DC-DC converter (DC). The loads are connected to the battery.

There are three control variables: the electric generator power P_e, the power through the DC-DC converter P_{dc} and the position of the switch s.

Independently from the position of the switch, the electric energy provided by the generator is equal to the sum of the powers to the load, the battery, and the supercap, and the power losses of the DC-DC converter.

2.2 Analysis

The possible benefits of a dual storage net are analyzed for the two positions of the switch.

Case $s = 0$

The generator is connected to the battery and the loads. This is the baseline situation. Additionally, the supercap can be charged and discharged through the DC-DC converter. Doing so is only beneficial if the losses of the supercap and the DC-DC converter together are smaller than the battery losses.

Case $s = 1$

The generator is connected to the supercap, so the supercap can be charged directly. The loads can be provided by the battery or by the combination of generator and DC-DC converter. It is only beneficial to use the switch in this position if the power that is stored in the supercap is larger than the power requested by the loads, because then, the losses of the DC-DC converter are smaller in this direction.

3. CONTROL OBJECTIVE AND CONSTRAINTS

The intention of energy management is to improve the fuel economy of the vehicle, so the control objective is to minimize the overal fuel consumption while satisfying several constraints. This can be described as an optimization problem:

$$\min_x J(x) \quad \text{subject to} \quad G(x) \leq 0 \tag{1}$$

The cost function J expresses the fuel use over a driving cycle as function of the design variables x. This way, the characteristics of all components can be combined into a singe cost function over a time interval $[0, t_e]$:

$$J(x) = \int_0^{t_e} P_f(x(t))\, \mathrm{d}t \tag{2}$$

For optimization it might be beneficial to choose the design variables x different from the control variables and to compute the corresponding values of the control variables afterwards.

The operating range of the components is limited, so bounds have to be set on their power and energy levels. To prevent the storage devices from being drained, endpoint constraints on the state of charge can be used.

4. MODELING

The dual storage power net control problem has been described as an optimization problem. Here, the relation between the design variables and the cost function is described which is needed to compute the solution.

The dynamics are modeled in discrete time. The component losses are modeled using piecewise linearities. This way, the problem can be written as a linear programming (LP) problem:

$$\min_x \; J(x) = h^T x \quad \text{subject to} \quad A\, x \leq b \tag{3}$$

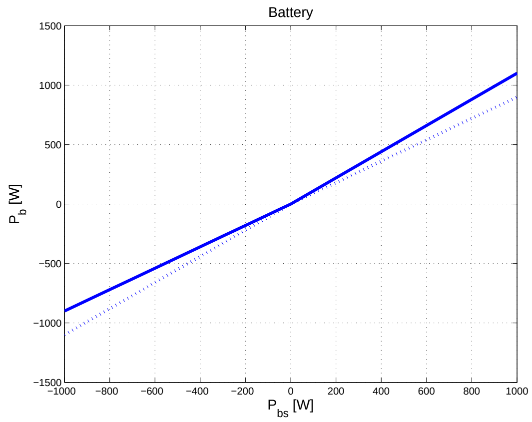

Fig. 2. Battery characteristics

which can be solved efficiently (Murty, 1983). A similar approach has been applied to a series hybrid vehicle in (Tate and Boyd, 2000).

Piecewise linear functions of the form:

$$x = \max(a_i\, y + b_i) \quad i = 1, \ldots, m \tag{4}$$

can be incorporated in a LP by adding secondary variables y together with inequality constraints:

$$\min_x \; h^T x \quad \text{subject to} \quad x \geq a_i\, y + b_i \tag{5}$$

If the objective is monotonically increasing with x, so $h > 0$, x will always be pushed on one of the constraints.

4.1 Components

The battery can be modeled as follows:

$$P_b = \max(b^- P_{bs}, b^+ P_{bs}) \tag{6}$$

where P_b represents the power entering or leaving the battery terminals, and P_{bs} represents the power actually stored in the battery. A typical curve is shown in Fig. 2. The losses are positive both during charging and discharging, so $b^+ > 1$ and $0 < b^- < 1$.

The model for the supercap is similar:

$$P_c = \max(c^- P_{cs}, c^+ P_{cs}) \tag{7}$$

The DC-DC converter is modeled likewise:

$$P_{db} = \max(d^- P_{dc}, d^+ P_{dc}) \tag{8}$$

where $P_{db} > 0$ means power is going from the battery to the supercap.

The characteristic of the generator is given by a nonlinear relation, that can be approximated linearly for given engine speed ω:

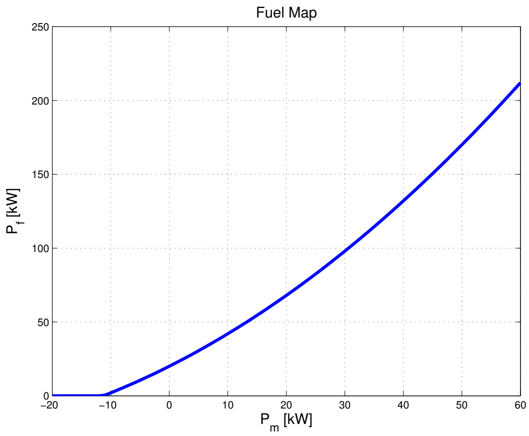

Fig. 3. Fuel map

$$P_g = g(P_e, \omega) \approx g_0(\omega) + g_1\,P_e \tag{9}$$

g_0 is caused by friction and g_1 is the inverse of the conversion efficiency, so $g_0 > 0$ and $g_1 > 1$.

The characteristics of the fuel converter is given by the following relation:

$$P_f = f(P_m, \omega) \tag{10}$$

where P_m is the mechanical power. A typical curve for a given engine speed ω is shown in Fig. 3.

Because the fuel map is convex, it can be described using m linear approximations, such that:

$$P_f \approx \max(f_{01} + f_{11}P_m, \ldots, f_{0m} + f_{1m}P_m) \tag{11}$$

4.2 Power flow

The mechanical power P_m is given by.

$$P_m = P_p + P_g + P_{br} \tag{12}$$

where P_{br} is the power of the friction brakes.

$P_{m\,min}(\omega)$ is the friction in the engine at zero fuel use. At moments where:

$$P_p < P_{m\,min} - g_0 \tag{13}$$

electric power can be generated without fuel use. This is called regenerative braking. It is expected that the friction brakes are only used when:

$$P_p < P_{m\,min} - P_{g\,max} \tag{14}$$

The equation for the electric power flow becomes:

$$\begin{aligned} P_e &= P_{eb} + P_{ec} \\ &= P_l + P_b + P_c + P_{db} - P_{dc} \end{aligned} \tag{15}$$

4.3 Design variables

Suppose the primary design variables are:

$$x_1 = [\ P_{bs}\ P_{cs}\ P_{dc}\ ]^T \tag{16}$$

The piecewise linear component models and the linear power flow equations can be incorporated by introducing the following secondary design variables:

$$\begin{aligned} x_2 = [\ & P_b\ P_c\ P_{db}\ P_{eb}\ P_{ec} \\ & P_e\ P_g\ P_m\ P_{br}\ P_f\ ]^T \end{aligned} \tag{17}$$

If optimization is done over a horizon of n time steps, the variables are vectors with length n, so the total number of design variables is $13\,n$.

4.4 Cost function

The cost function is the fuel consumption over a driving cycle with length $t_e = n\,\Delta t$:

$$J(x) = \sum_{i=1}^{n} P_f(i)\,\Delta t \tag{18}$$

4.5 Constraints

The power flow equations are incorporated as linear equality constraints:

$$P_{eb} = P_l + P_b + P_{db} \tag{19}$$
$$P_{ec} = P_c - P_{dc} \tag{20}$$
$$P_e = P_{eb} + P_{ec} \tag{21}$$
$$P_m = P_p + P_g + P_{br} \tag{22}$$

The piecewise linear component models are incorporated using the following constraints:

$$P_b \geq b^{\pm}\,P_{bs} \tag{23}$$
$$P_c \geq c^{\pm}\,P_{cs} \tag{24}$$
$$P_{db} \geq d^{\pm}\,P_{dc} \tag{25}$$
$$P_g = g_0 + g_1\,P_e \tag{26}$$
$$P_f \geq f_{0i} + f_{1i}\,P_m \tag{27}$$

The physical limitations of the components are incorporated using upper and lower bounds on the design variables:

$$x_{min} \leq x \leq x_{max} \tag{28}$$

The constraints on the energy storage levels are incorporated using a discrete linear integrator model:

$$E_{*s}(k) = E_{*s}(0) + \sum_{i=1}^{k} P_{*s}(i)\,\Delta t \qquad (29)$$

The endpoint constraints then become:

$$E_{*s}(n) = E_{*s}(0) \quad \Rightarrow \quad \sum_{i=1}^{n} P_{*s}(i) = 0 \quad (30)$$

4.6 Complementarity constraint

The discrete switch can be modeled by adding a complementarity constraint:

$$P_{eb} \cdot P_{ec} = 0 \qquad (31)$$

The LP problem with complementarity constraint for the discrete switch can be translated to a mixed integer LP problem by introducing a binary variable $s \in \{0, 1\}$ and adding the following linear constraints:

$$0 \leq P_{eb} \leq (1 - s)\, P_{eb\,max} \qquad (32)$$

$$0 \leq P_{ec} \leq \quad s\;\, P_{ec\,max} \qquad (33)$$

Note that $s = 0$ yields that $P_{ec} = 0$ and $s = 1$ yields that $P_{eb} = 0$, which corresponds with the two positions of the switch.

5. GLOBAL OPTIMIZATION

For the continuous switch, the optimization problem can be solved with a standard LP solver. The problem is very sparse, so despite the large number of design variables, the computation time remains short.

For the discrete switch, a mixed integer LP solver can be used, e.g., a branch and bound algorithm. The computation time of mixed integer solvers increases drastically with the number of discrete variables, because the algorithms evaluate many combinations of these variables. This makes mixed integer optimization not suitable for optimization over a long horizon.

A suboptimal mixed integer solution can be obtained as follows. First the problem is solved for the continuous switch. Then the position of the switch is rounded off to boolean values. The continuous optimization is repeated, but with the upper bounds modified according to (32) and (33).

6. REALTIME CONTROL STRATEGY

A control strategy is derived that can be used in real time. It is similar to the method for a single storage system as presented in (Koot *et al.*, 2004).

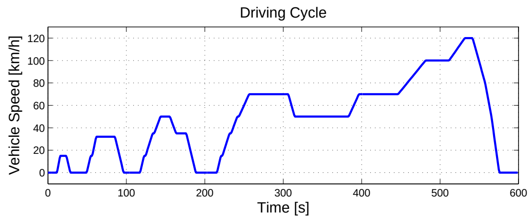

Fig. 4. Driving Cycle

Optimization is done at each time instant with a horizon length of 1 time step. Instead of using endpoint constraints on the storage levels, the change in SOC is accounted for in the cost function:

$$\min_{x}\; J(x) \;=\; P_f - \lambda_b\, P_{bs} \;-\lambda_c\, P_{cs} \qquad (34)$$

At each time instant, a trade off is made between the increase in fuel and the increase in SOC. All other constraints still apply.

The factors λ_b and λ_c represent the average fuel costs to store energy in the battery and the supercap. They are adapted online using proportional state feedback:

$$\lambda_* = \lambda_{*0} + K_p\, (E_{*s} - E_{*s}(0)) \qquad (35)$$

The state feedback ensures that the SOC remains bounded, although the SOC at the end will differ from the beginning. The changes in SOC are accounted for in the fuel consumption using the initial values of λ_b and λ_c.

For the discrete switch, the optimization has to be carried out twice at each time instant. Once with $P_{eb} = 0$ and once with $P_{ec} = 0$. The solution with the lowest cost function value is then selected.

7. SIMULATIONS

7.1 Model

Simulations are done for a mid-sized vehicle, of which a detailed description can be found in (Koot *et al.*, 2004). The specifications of the electric components are shown in Table 1.

Table 1. Power net components

	Capacity	Power limits	Efficiency
Battery	1000 kJ	2 kW	90%
Supercap	100 kJ	5 kW	99%
DC-DC	-	2 kW	95%
Generator	-	5 kW	90%

Simulations are done for the last 600 seconds of the NEDC cycle, of which the velocity profile is shown in Fig. 4. The electric load is kept constant at 1000 W.

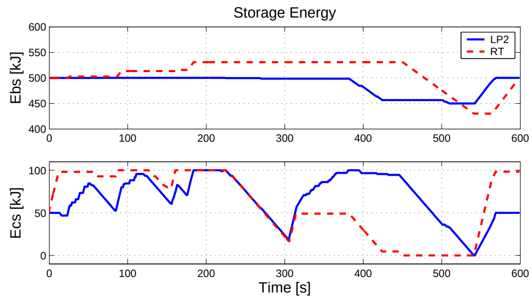

Fig. 5. State of charge

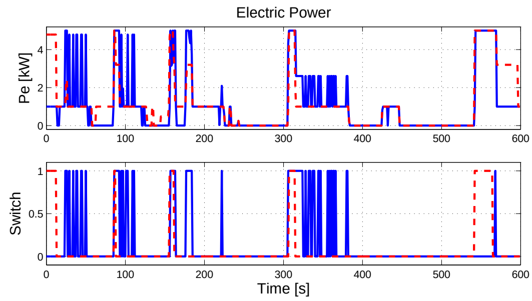

Fig. 6. Electric power and switch position

7.2 Results

The following strategies are implemented:

- BL1 A baseline strategy that does not use the storage devices, so the generator power is equal to the load
- BL2 A baseline strategy that only uses the battery.
- LP1 Continuous LP optimization of the complete cycle.
- LP2 Sub-optimal mixed integer LP optimization of the complete cycle.
- RT The realtime strategy.

The SOC trajectories for the LP2 and RT strategies are shown in Fig. 5. Fig. 6 shows the corresponding electric power and the position of the switch. The switch is used when much electric power is generated during deceleration. The battery is mainly used during the braking period at the end, when the supercap hits its boundary.

The power levels change rapidly. This is typical for LP since the optimal solution will always lie at a constraint. Smoother behavior can be obtained by adding rate limiting constraints, or by using quadratic terms for the losses, resulting in a QP.

The fuel saving percentages with respect to the BL1 strategy are given in Table 2. The absolute numbers are the savings on the total fuel consumption. The relative numbers are the savings on the fuel needed for the electric power. Because there is no control freedom in the drive train and the fuel map is monotonically increasing, the fuel consumption needed for propulsion is fixed.

Although the SOC trajectories of LP2 and RT show large deviations, the difference in fuel consumption is small.

Table 2. Fuel Savings

Saving [%]	Absolute	Relative
BL2	1.58	19.7
LP1	2.62	32.8
LP2	2.54	31.8
RT	2.56	32.0

8. DISCUSSION

Simulations show that the control strategies are working and that the performance of the realtime strategy is close to the optimal one.

For the chosen parameter values, the dual storage power net gives a significant improvement in fuel reduction over the single storage net.

The approach can be extended to a hybrid electric vehicle, where the energy obtained with regenerative braking can be used for starting the engine and propulsion.

Linear Programming is a powerful tool for this application. Because of its simple structure, the method is easy to apply on other topologies.

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